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Review Article

Critical review of the literature on key invasive alien freshwater plants in Europe with special focus on their impact on the invaded ecosystems

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Abstract

Biological invasions of alien aquatic plants are a major threat to conservation of freshwater habitats, as well as a socio-economic problem. Introduced primarily by human activities, these alien plants compete with native species, reduce local biodiversity and alter structure and function of the aquatic ecosystems. This review examines the most relevant scientific literature on the major invasive alien aquatic plants (IAAPs) found in Europe (*Alternanthera philoxeroides*, *Azolla filiculoides*, *Cabomba caroliniana*, *Egeria densa*, *Elodea canadensis*, *E. nuttallii*, *Gymnocoronis spilanthoides*, *Hydrilla verticillata*, *Hydrocotyle ranunculoides*, *Lagarosiphon major*, *Lemna minuta*, *Ludwigia grandiflora*, *L. hexapetala*, *L. peploides* subsp. *montevidensis*, *Myriophyllum aquaticum*, *M. heterophyllum*, *Pistia stratiotes*, *Pontederia crassipes*, *Salvinia molesta*), with a special focus on impacts exerted by these species on invaded freshwater ecosystems. It includes both qualitative and quantitative analyses and evaluates the temporal trends of the scientific contributions considering the impact and management of these species in Europe and worldwide. Despite a recent increase in contributions on these IAAPs, the knowledge on their impacts in Europe remains mainly concentrated on a few species and rather fragmented and deficient on others. In fact, evident inequalities emerge among these IAAPs in both the number of dedicated contributions and in the treatment of each species, as some of them are currently excluded from the list of IAS of Union Concern. Moreover, the European level research on these IAAPs turned out to be scarcely influenced by the "listing" effect (i.e. inclusion of IAAPs in the Union list), showing little or no increase in the number of studies on impact or management. The studies found on impacts document that the selected IAAPs largely exert environmental impacts on invaded ecosystems by altering both the abiotic (water chemical and physical factors) and biotic (plant and animal communities) components. The impact mechanisms of these species vary (chemical, physical, structural, competitive, toxicity) and were classified according to the EICAT (Environmental Impact Classification for Alien Taxa) protocol. Overall, the review reveals significant gaps in knowledge about the environmental impacts of most of these IAAPs in Europe, despite some being included in the list of IAS of Union concern. To address these gaps and protect European freshwater ecosystems from biological invasions, more field studies supported by laboratory investigations are needed, followed by effective management interventions. In addition, it is considered necessary that impactful alien species with a wide distribution in Europe, but which are currently excluded from the EU list, be included as soon as possible. This would allow for coordinated management practices at the European level, which are essential for their containment.

Key words: Bibliographic overview, biological invasions, ecosystem impact, Europe, exotic plants, freshwater ecosystems, invasive macrophytes, non-native plants, vascular plants

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Introduction

Freshwater ecosystems cover 0.8% of the Earth's surface and contain just 0.01% of its water (Dudgeon et al. 2006). Nevertheless, these are significant for their high biodiversity and numerous ecosystem services that they provide, primarily benefiting humans (Strayer and Dudgeon 2010; Hoppenreijs et al. 2024). Dynamic and vulnerable, freshwater ecosystems face frequent disturbances from anthropogenic pressures, such as hydrological and morphological alterations, water over-exploitation and pollution, leading to significant environmental instability. Such instability makes them highly susceptible to biological invasions, that is the spread of invasive alien species (IAS) outside their home range (Dudgeon et al. 2006; Anufriieva and Shadrin 2018; Lazzaro et al. 2020). Invasive alien plants typically thrive in altered environments due to their competitiveness, wide ecology and high reproductive potential (Perrings et al. 2000; Mazza et al. 2014). They outcompete native species, reducing local biodiversity (Pyšek et al. 2012; Viciani et al. 2020), and altering the structure and functionality of invaded ecosystems, and ultimately compromising their conservation status (Maes 2013; Seebens et al. 2017).

In Europe, freshwater ecosystems are among the most heavily invaded by alien plants (Lazzaro et al. 2020), resulting in severe ecological and socio-economic consequences (Vilà et al. 2010; Hussner 2012). These plant invasions are often associated with the production of high biomass, which translates into various environmental impacts, such as changes in water chemistry and physical properties of the invaded ecosystem, alterations in the composition and biodiversity of native plant and animal communities, modifications in the structure of the food webs (Hussner et al. 2017). Furthermore, these invasions can cause socio-economic impacts, such as hindering navigation, aquaculture, and recreational activities, as well as creating unhealthy conditions for local plant and animal communities and human health (Stiers et al. 2011; Hussner 2012; Ceschin et al. 2020a). Macêdo et al. (2024) recently reported that between 1975 and 2020, the total cost to the global economy for the overall management of alien aquatic plants has exceeded 32 billion dollars. This highlights not only the importance of the problem, but also its relevant economic impact on a global scale.

In response to the significant increase in biological invasions in Europe over the last decades, in 2014 the European Community approved the European Union (EU) Regulation 1143/2014/EC on IAS (IAS Regulation) that establishes a coordinated set of actions to prevent, control and mitigate the impact of the IAS. In 2016, the European Community drew up a list of IAS of Union concern which serves to direct research and management efforts (European Union 2016). With the latest update (European Union 2022), the list includes 41 alien plants, among which 13 are strictly freshwater species, including *Alternanthera philoxeroides* (Mart.) Griseb., *Cabomba caroliniana* A.Gray, *Pontederia crassipes* Mart. (= *Eichhornia crassipes* (Mart.) Solms), *Elodea nuttallii* (Planch.) H.St.John, *Gymnocoronis spilanthoides* (D.Don ex Hook. and Arn.) DC., *Hydrocotyle ranunculoides* L.f., *Lagarosiphon major* (Ridl.) Moss, *Ludwigia grandiflora* (Michx.) Greuter and Burdet, *L. peploides* (Kunth) P.H.Raven subsp. *montevidensis* (Spreng.) P.H.Raven, *Myriophyllum aquaticum* (Vell.) Verdc., *M. heterophyllum* Michx., *Pistia stratiotes* L. and *Salvinia molesta* D.S.Mitch. Species included in this list cannot be either released into the environment or traded or cultivated in any European Community country (European Union

2014). However, this European list excludes some widespread aquatic plants considered as invasive neophytes in several European countries, such as *Azolla filiculoides* Lam., *Egeria densa* Planch., *Elodea canadensis* Michx., *Hydrilla verticillata* (L.f.) Royle, *Lemna minuta* Kunth and *Ludwigia hexapetala* (Hook. and Arn.) Zardini, H.Y.Gu and P.H.Raven (Ceschin et al. 2018a; Galasso et al. 2018; Magliozzi et al. 2020; Arianoutsou et al. 2023; Oficialdegui et al. 2023; Pelella et al. 2023a). In this background, the present investigation is aimed to (i) collect and critically review the relevant scientific literature on the invasive alien aquatic plants (IAAPs) occurring in Europe, and (ii) assess the current state of knowledge regarding their impact on invaded European freshwater ecosystems, with special focus on environmental impact. This review may highlight any gaps in knowledge on the environmental impacts exerted by these species in Europe. In addition, it may also provide a basis for directing future investigations into those IAAPs that are understudied.

Methods

IAAPs selection

Bibliographic research focused on both IAAPs that are included in the European list of IAS of Union concern (European Union 2016, and subsequent updates), and some alien aquatic plants that, although outside this list, are widespread in European freshwater ecosystems based on distribution data extracted from Global Biodiversity Information Facility (GBIF 2023). In particular, the following 19 IAAPs were selected: *Alternanthera philoxeroides*, *Cabomba caroliniana*, *Elodea nuttallii*, *Gymnocoronis spilanthoides*, *Hydrocotyle ranunculoides*, *Lagarosiphon major*, *Ludwigia grandiflora*, *L. peploides* subsp. *montevidensis* (thereafter *L. peploides*), *Myriophyllum aquaticum*, *M. heterophyllum*, *Pistia stratiotes*, *Pontederia crassipes*, *Salvinia molesta* (IAAPs in EU list), and *Azolla filiculoides*, *Egeria densa*, *Elodea canadensis*, *Hydrilla verticillata*, *Lemna minuta*, *Ludwigia hexapetala* (IAAPs out EU list) (Table 1).

Bibliographic research

Bibliographic data sources

Bibliographic research on the selected IAAPs was conducted using the online database Web of Science (WOS) (Clarivate Analytics 2023), considering worldwide distributed scientific contributions. In the research string, the keywords included for each species both scientific names (including all synonyms) and common English names, both taken from GBIF (2023), as well as the following terms: "alien*", "allochthonous", exotic*", "introduc*", "IAS", "invas*", "non-indigenous plant", "non-indigenous species", "non-native plant", "non-native species" and "impact*", "damage*", "reduc*", "extinct*", "allelopathic", "inhibit*", "alter*", "control", "compet*".

The contributions were selected based on the following criteria: (i) accessible on the web, (ii) published in international peer-reviewed journals indexed in WOS, (iii) written in English, (iv) published up to November 2023, and (v) based on field and/or laboratory studies, excluding forecasting or simulation studies.

The collected contributions for each species were grouped based on the main topic addressed (thereafter macrotopic). Ten main macrotopics were identified:

- "impact" macrotopic: contributions addressing the impact exerted by the selected IAAPs on the invaded ecosystem;
- "management" macrotopic: contributions analyzing the various methods tested to manage the IAAPs;
- "distribution" macrotopic: contributions with data, floristic records or distribution maps of the species considered;
- "ecology", "biology", "physiology" and "genetics" macrotopics: contributions related to these aspects, respectively;
- "uses" macrotopic: contributions exploring potential uses of the species (e.g., as bioenergy source, biofood, bioindicator, phytoremediation agent);
- "general" and "other": in "general" were included the more generalist contributions that reference three or more macrotopics without a specific focus on any one in particular, whereas in "other" the contributions with topics different from those mentioned above.

Data collection

For each scientific contribution collected, the following information was extracted, creating a digital database in Excel (Excel vers. 2409, Microsoft Corporation 365):

- scientific name of the aquatic plant considered as alien in that contribution (2023);
- year of publication;
- main macrotopic addressed. Contributions referring to two different but equally addressed macrotopics were attributed to both, resulting in being counted twice in the final count of contributions considered.

Specifically with regard to contributions on the "impact" and "management" macrotopics, the following information was also specified:

Area of study	– Study area within or outside Europe
Type of study	– Laboratory study (indoor, microcosms, greenhouse) – Field study (outdoor, mesocosms, nature)
Type of impact	– Socio-economic impact on society and local economy (e.g., public health issues, waterbody landscape alteration, aesthetic degradation, limitations on aquaculture, fishing, tourism, and high management costs) – Environmental impact (on abiotic and/or biotic component of the ecosystem)
Impact environmental mechanism[1]	– On abiotic component (chemical, physical)

1 Categorization of mechanisms of environmental impact following the classification proposed by the IUCN (International Union for Conservation of Nature) in the EICAT (Environmental Impact Classification for Alien Taxa) protocol (Hawkins et al. 2015).

	– On native biotic component (competition, direct physical disturbance, hybridization, structural, toxicity)
Management methods	– Prevention
	– Control method (chemical, physical, biological)

Data analysis

The scientific contributions resulting from the bibliographic research were analyzed according to points indicated in the section "Data collection". The results of these analyses were shown in graphs and tables created using Microsoft Excel vers. 2409 (Microsoft Corporation 365). The total number of scientific contributions produced up to November 2023, and the average percentage of contributions falling within each of the 10 macrotopics, were calculated both considering all species together that for each IAAPs.

For the macrotopic on impact, the percentage of contributions addressing different types of impact (socio-economic, environmental) was also calculated. In addition, to assess the temporal trend of the scientific production concerning this macrotopic on a global and European scale, the year of publication of each contribution was considered within five 8-year intervals (1984–1991, 1992–1999, 2000–2007, 2008–2015, 2016–2023), with the first interval determined based on the dates of the earliest contributions found. The last time interval considered includes the year 2016, which marks the publication date of the first list of IAS of Union concern. A similar temporal analysis was conducted for contributions related to the macrotopic on management of the selected IAAPs to verify any consistency in the temporal trend between the number of contributions published on the impact of these species and those dedicated to their management. In addition, a correlation analysis was carried out using R software (R Core Team 2023) to assess the relationship between the number of European countries invaded by IAAPs and the scientific contributions on the impact found on globally for each species. Pearson's correlation coefficient was calculated using the cor. test function, obtaining both correlation value (r) and statistical significance (p value).

Results

Bibliographic analysis

Based on the bibliographic analysis of the 19 IAAPs, 1918 scientific contributions published up to November 2023 in international peer-reviewed journals and indexed in WOS were collected. The analysis identified ecological and management studies as the most investigated macrotopics, representing 27.1% and 20.7% of the contributions, respectively. Secondarily, there were studies on the distribution (11.5%), uses (11.2%) and impact (10.5%) of these alien species. Each of the remaining macrotopics accounted for less than 7% of the total scientific contributions collected (Fig. 1).

The in-depth analysis of the contributions referring to impacts exerted by the 19 IAAPs showed that 77% of the studies have a worldwide distribution, while the remaining 24% refer specifically to studies carried out in European countries. Of the worldwide contributions on impact, 81.2% (181) focus on the environmental impact, while the remaining 18.8% (42) on socio-economic impact. Among the studies on environmental impact, 70.5% (155) document impacts on biotic components (e.g.,

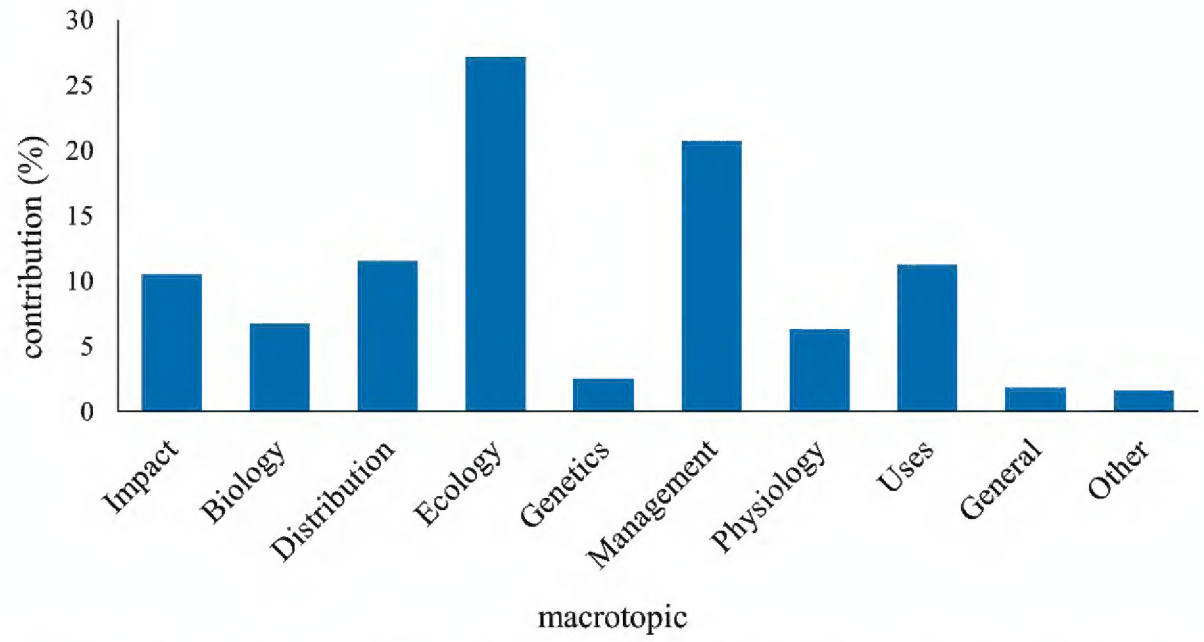

Figure 1. Percentages of scientific contributions on the selected IAAPs in relation to the 10 macrotopics considered.

microalgae, macrophytes, macroinvertebrates, aquatic birds) of the invaded aquatic ecosystems, while 29.5% (65) reveals impacts on abiotic components, such as physical and chemical factors (e.g., temperature, light, pH, dissolved oxygen, nutrients). 64.6% (128) of the contributions on environmental impact referred to field studies, while 35.4% (70) to indoor experiments performed in the laboratory or greenhouses.

Over time, scientific production regarding the impact of the selected IAAPs showed a significant upward trend. Worldwide contributions increased exponentially ranging from the earliest time interval analyzed (1984–1991) to the latest (2016–2023), when the highest percentage of contributions (63.4%, 123 contributions) was recorded (Fig. 2a). A similar trend can be observed when considering only contributions on the impact studies produced in Europe. Indeed, in the last period, also coinciding with the inclusion of some of the IAAPs considered in the list of Union concern, most of the contributions produced on impact are concentrated. Similarly, contributions on the management of these species produced at both global and European level, have also grown progressively over time, with most studies (49.4%, 167) concentrated in the most recent time interval (Fig. 2b).

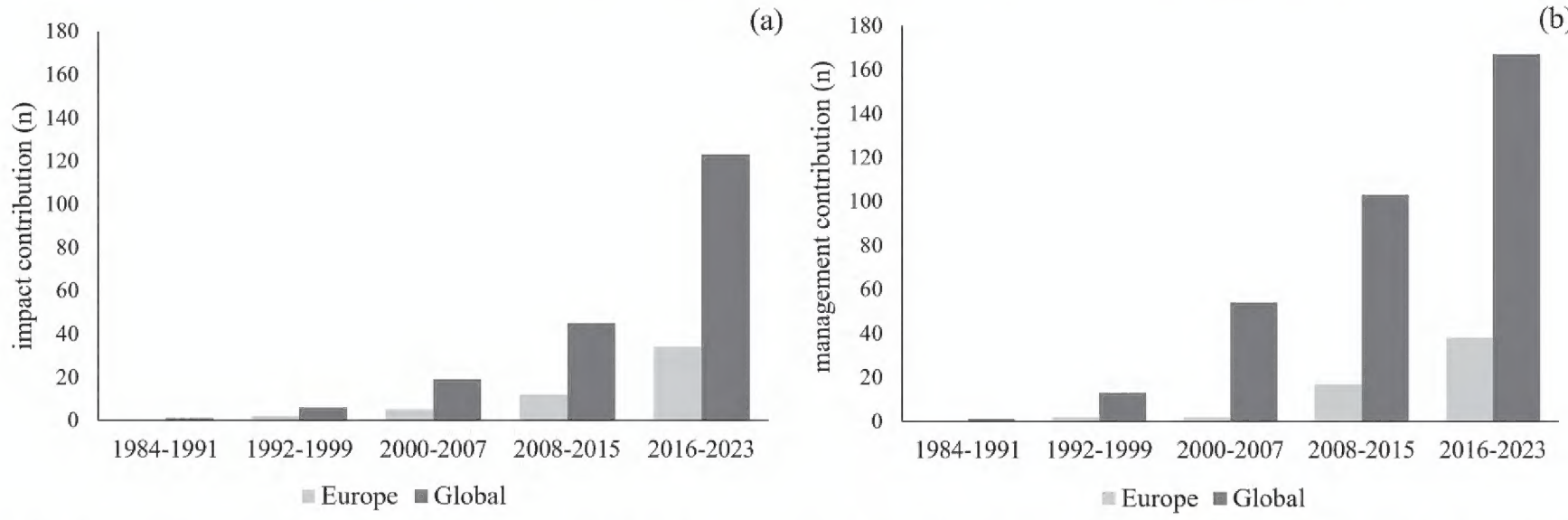

Figure 2. Temporal trends in the number of scientific contributions related to the impact (**a**) and management (**b**) of the selected IAAPs.

Bibliographic analysis for each IAAPs

Out of the 1918 scientific contributions collected in this review, about 64% are concentrated on 4 of the 19 selected IAAPs. In particular, *P. crassipes* (22.9%, 440 contributions), *A. philoxeroides* (16.3%, 312), *E. densa* (14.1%, 270) and *H. verticillata* (10.5%, 201) were proven to be the IAAPs most studied globally. In

contrast, *C. caroliniana* (2%, 38), *L. peploides* (1.8%, 34), *L. minuta* (1.4%, 27), *L. grandiflora* (1.2%, 23), *H. ranunculoides* (1%, 19), *M. heterophyllum* (0.8%, 16) and *G. spilanthoides* (0.3%, 5) were the least studied ones (Fig. 3). Generally, the most represented macrotopics for most of the species refer to ecological and management studies, except for *L. minuta*, which showed a proportionally high number of contributions on the impact (Table 1).

Correlating the number of European countries invaded from each of the considered IAAPs (index of species spread in Europe) with the total number of stud-

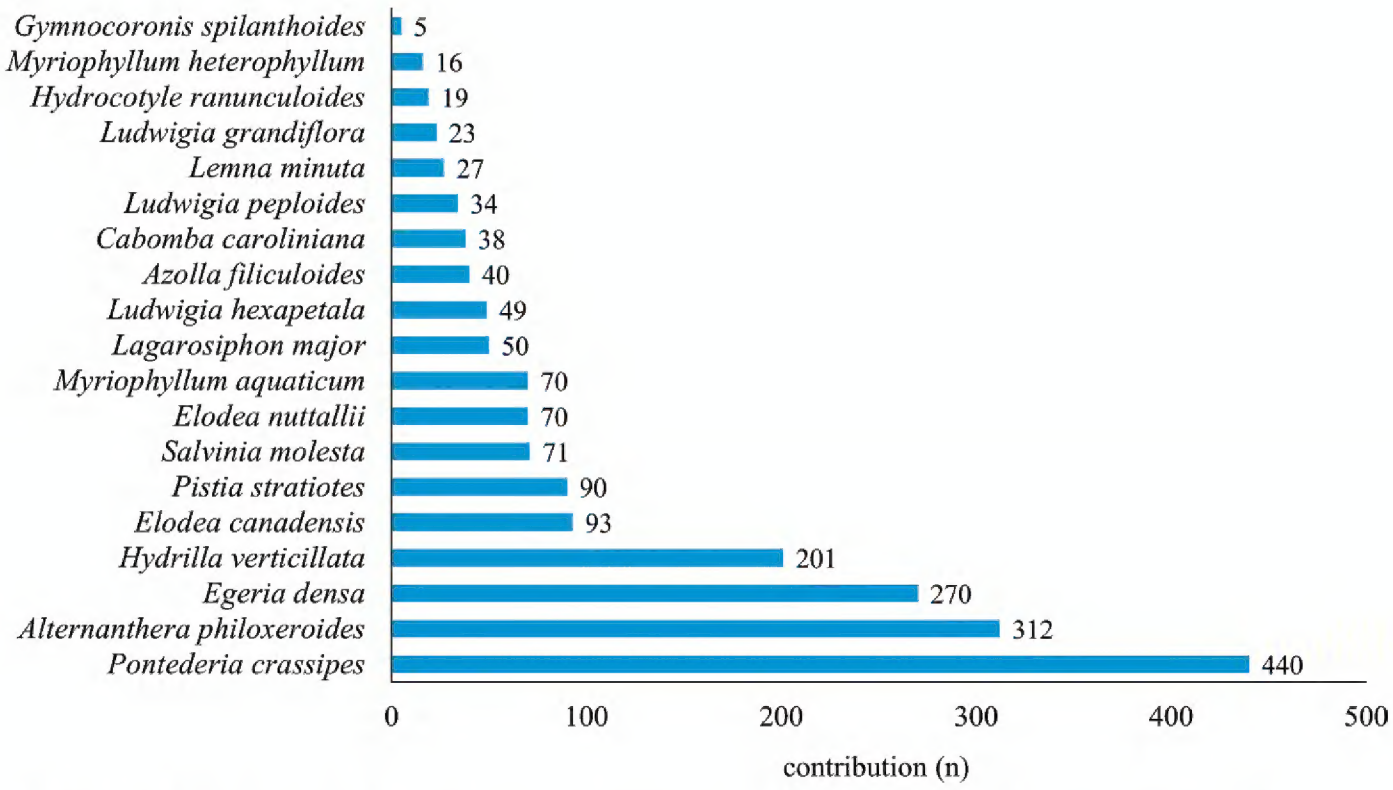

Figure 3. Total number of scientific contributions found for each of the 19 selected IAAPs.

Table 1. For each IAAPs, it is indicated whether the alien species is included (in, grey colour) or not (out, white colour) in the list of IAS of Union concern, the total number (n) and percentage (%) of scientific contributions related to the different macrotopics. In bold, contribution number ≥ 20.

UE list	IAAP	Impact	Biology	Distribution	Ecology	Genetics	Management	Physiology	Uses	General	Other
in	*Alternanthera philoxeroides*	**36 (11.0%)**	**65 (19.8%)**	**24 (7.3%)**	**113 (34.5%)**	18 (5.5%)	**32 (9.8%)**	**22 (6.7%)**	16 (4.9%)	2 (0.6%)	-
out	*Azolla filiculoides*	4 (9.5%)	3 (7.1%)	7 (16.7%)	5 (11.9%)	-	15 (35.7%)	-	8 (19.0%)	-	-
in	*Cabomba caroliniana*	4 (9.8%)	1 (2.4%)	7 (17.1%)	8 (19.5%)	2 (4.9%)	10 (24.4%)	6 (14.6%)	-	3 (7.3%)	-
out	*Egeria densa*	**20 (7.1%)**	7 (2.5%)	**22 (7.8%)**	**106 (37.5%)**	8 (2.8%)	**32 (11.3%)**	**47 (16.6%)**	**25 (8.8%)**	1 (0.4%)	15 (5.3%)
out	*Elodea canadensis*	6 (6.1%)	2 (2.0%)	19 (19.2%)	**49 (49.5%)**	4 (4.0%)	9 (9.1%)	4 (4.0%)	3 (3.0%)	2 (2.0%)	1 (1.0%)
in	*Elodea nuttallii*	10 (13.0%)	5 (6.5%)	12 (15.6%)	**33 (42.9%)**	1 (1.3%)	12 (15.6%)	2 (2.6%)	2 (2.6%)	-	-
in	*Gymnocoronis spilanthoides*	-	-	-	4 (80.0%)	-	-	-	-	-	1 (20.0%)
out	*Hydrilla verticillata*	**31 (14.9%)**	9 (4.3%)	17 (8.2%)	**54 (26.0%)**	7 (3.4%)	**57 (27.4%)**	10 (4.8%)	12 (5.8%)	3 (1.4%)	8 (3.8%)
in	*Hydrocotyle ranunculoides*	3 (15.0%)	1 (5.0%)	4 (20.0%)	4 (20.0%)	1 (5.0%)	5 (25.0%)	-	1 (5.0%)	1 (5.0%)	-
in	*Lagarosiphon major*	7 (13.7%)	1 (2.0%)	5 (9.8%)	17 (33.3%)	1 (2.0%)	18 (35.3%)	1 (2.0%)	-	1 (2.0%)	-
out	*Lemna minuta*	9 (31.0%)	2 (6.9%)	5 (17.2%)	8 (27.6%)	2 (6.9%)	1 (3.4%)	1 (3.4%)	1 (3.4%)	-	-
in	*Ludwigia grandiflora*	3 (13.0%)	1 (4.3%)	2 (8.7%)	6 (26.1%)	1 (4.3%)	6 (26.1%)	3 (13.0%)	-	-	1 (4.3%)
out	*Ludwigia hexapetala*	8 (15.4%)	7 (13.5%)	5 (9.6%)	16 (30.8%)	-	10 (19.2%)	4 (7.7%)	1 (1.9%)	1 (1.9%)	-
in	*Ludwigia peploides*	1 (2.9%)	4 (11.4%)	6 (17.1%)	12 (34.3%)	-	5 (14.3%)	4 (11.4%)	2 (5.7%)	1 (2.9%)	-
in	*Myriophyllum aquaticum*	4 (5.4%)	6 (8.1%)	6 (8.1%)	**26 (35.1%)**	-	18 (24.3%)	5 (6.8%)	4 (5.4%)	5 (6.8%)	-
in	*Myriophyllum heterophyllum*	4 (25.0%)	-	2 (12.5%)	5 (31.3%)	1 (6.3%)	3 (18.8%)	1 (6.3%)	-	-	-
in	*Pistia stratiotes*	3 (3.0%)	7 (7.0%)	12 (12.0%)	19 (19.0%)	2 (2.0%)	**32 (32.0%)**	2 (2.0%)	**20 (20.0%)**	2 (2.0%)	1 (1.0%)
in	*Pontederia crassipes*	**54 (11.3%)**	9 (1.9%)	**72 (15.1%)**	**59 (12.4%)**	1 (0.2%)	**125 (26.3%)**	17 (3.6%)	**123 (25.8%)**	12 (2.5%)	4 (0.8%)
in	*Salvinia molesta*	7 (9.1%)	7 (9.1%)	7 (9.1%)	8 (10.4%)	2 (2.6%)	**31 (40.3%)**	-	11 (14.3%)	2 (2.6%)	2 (2.6%)

ies carried out in the world on their impact, no correlation between the two variables is emerged ($r = -0.15$, $p > 0.05$, Pearson correlation coefficient) since the most widespread species in Europe are not always those whose impact was most studied (Table 2). In fact, some of the alien aquatic species that are common in Europe ($n \geq 12$, high number of European countries invaded) prove to be little studied in the world (e.g. *Elodea canadensis*, *Azolla filiculoides*, *Myriophyllum aquaticum*, *Pistia stratiotes*); on the other hand, some species that do not show wide European distribution ($n \leq 11$, medium-low number of European countries invaded), have had many studies on their impact (e.g., *Alternanthera philoxeroides*, *Egeria densa*, *Pontederia crassipes*).

Table 2. Number of European countries invaded by each selected IAAPs and total number of scientific contributions extracted from the literature concerning their impact on invaded ecosystem. Distribution data of each IAAP within were obtained from GBIF (2023). Acronyms of European countries: Austria (AT), Belgium (BE), Bulgaria (BG), Switzerland (CH), Czech Republic (CZ), Germany (DE), Denmark (DK), Spain (ES), Finland (FI), France (FR), Greece (GR), Croatia (HR), Hungary (HU), Ireland (IE), Italy (IT), Lithuania (LT), Latvia (LV), Netherlands (NL), Poland (PL), Portugal (PT), Romania (RO), Sweden (SE), Slovakia (SK), United Kingdom (UK).

IAAP	Invaded EU countries	countries (n)	impact contributions (n)
Alternanthera philoxeroides	ES, FR, IT, NL, PT	5	36
Azolla filiculoides	AT, BE, CZ, DE, DK, ES, FR, GR, HU, IE, IT, NL, PL, PT, RO, SE, UK	17	4
Cabomba caroliniana	BE, CH, DE, DK, FR, HU, NL, PL, RO, SE, UK	11	4
Egeria densa	BE, CZ, DE, ES, FR, IE, IT, NL, PT, UK	10	20
Elodea canadensis	AT, BE, BG, CH, DE, DK, ES, FI, FR, HU, IE, IT, NL, PL, PT, RO, SE, UK	18	6
Elodea nuttallii	AT, BE, BG, CH, DE, DK, ES, FI, FR, HU, IE, IT, LT, NL, PL, RO, SE, UK	18	10
Gymnocoronis spilanthoides	HU, IT, NL, SE	4	-
Hydrilla verticillata	AT, CH, DE, ES, FR, IE, IT, LT, LV, PL, UK	11	31
Hydrocotyle ranunculoides	BE, CH, DE, DK, ES, FR, HU, IE, IT, NL, UK	11	3
Lagarosiphon major	AT, BE, CH, DE, FR, IE, IT, NL, PT, UK	10	7
Lemna minuta	AT, BE, CH, DE, ES, FR, IE, IT, NL, PL, PT, RO, UK	13	9
Ludwigia grandiflora	AT, BE, CH, ES, FR, HU, IE, IT, NL, PT, UK	11	3
Ludwigia hexapetala	BE, ES, FR, HU, IT, PT, UK	7	8
Ludwigia peploides	BE, ES, FR, IT, NL, PT	6	1
Myriophyllum aquaticum	AT, BE, CH, DE, ES, FR, IE, IT, NL, PT, RO, UK	12	4
Myriophyllum heterophyllum	AT, BE, CH, DE, ES, FR, HU, NL, SE, UK	10	4
Pistia stratiotes	BE, CH, DE, ES, FR, HR, IT, NL, PL, SE, SK, UK	12	3
Pontederia crassipes	BE, DE, ES, FR, HU, IT, NL, PL, PT, UK	10	54
Salvinia molesta	AT, BE, CH, DE, ES, FR, HU, IT, NL, PT	10	7

The average number of contributions on the impact of IAAPs included and not-included in the list of the IAS of Union concern is 10.5 and 13.0 globally, and 2.3 and 4.0 for Europe, respectively (Fig. 4). The IAAPs included in the list result averagely less studied than those not-included, both at the global and European level, except for *P. crassipes* and *A. philoxeroides*, which far exceed these averages when considering global studies.

By comparing the number of European studies on the impact and management of the IAAPs included in the Union list and the year in which each of these was included in this list (Table 3), it emerged that in most species, the number of studies on impact increased little after these were listed (minimal listing effect). In some cases, a lower number of studies was also recorded after inclusion in the list (*E. nuttallii*, *L. grandiflora*, *L. peploides*, *P. stratiotes*, *S. molesta*), or even no

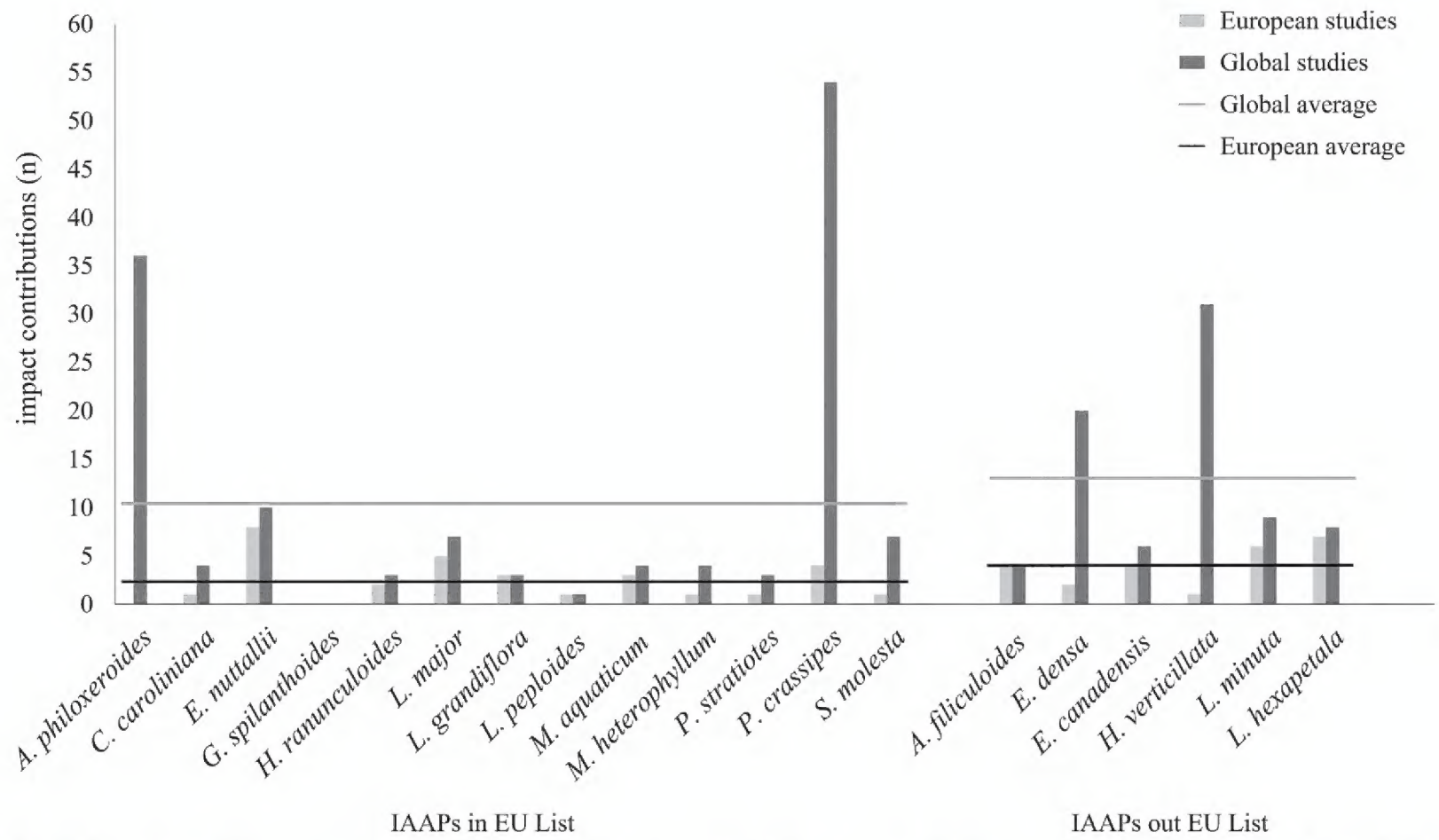

Figure 4. Number of scientific contributions on the impact of the IAAPs included and not-included in the list of the IAS of Union concern. The black horizontal lines mark the average number of contributions for each IAAP group.

Table 3. For each species included in the list of IAS of Union concern, the year of its inclusion and the number of scientific European contributions on its impacts and management were reported. Species are listed according to the year of their inclusion in the EU list.

IAAP	year of inclusion in EU list	EU impact contributions		EU management contributions	
		before list	after list	before list	after list
Cabomba caroliniana	2016	-	1	-	1
Hydrocotyle ranunculoides	2016	1	1	1	2
Lagarosiphon major	2016	1	4	5	6
Ludwigia grandiflora	2016	2	1	1	2
Ludwigia peploides	2016	1	-	1	-
Myriophyllum aquaticum	2016	1	2	1	2
Pontederia crassipes	2016	1	3	-	3
Alternanthera philoxeroides	2017	-	-	-	1
Elodea nuttallii	2017	5	3	3	7
Myriophyllum heterophyllum	2017	-	1	-	-
Gymnocoronis spilanthoides	2019	-	-	-	-
Salvinia molesta	2019	1	-	-	-
Pistia stratiotes	2022	1	-	-	-

contribution was dedicated either before or after (*A. philoxeroides*, *G. spilanthoides*) (no listing effect). As regards the contributions relating to the management of the IAAPs included in the list, it appears that in most cases, the number of contributions increased slightly after these species were included in the list (minimal listing effect). However, also in this case, there are species that were not investigated either before or after their inclusion in the list (*G. spilanthoides*, *M. heterophyllum*, *P. stratiotes*, *S. molesta*) (no listing effect).

The 19 considered IAAPs were grouped into nine groups based on systematic affinity or morpho-structural similarity. A detailed description of the selected IAAPs, taking into account the main scientific contributions about them, is given below.

Lemna minuta, *Pistia stratiotes* (Araceae – free-floating hydrophytes)

Both *L. minuta* and *P. stratiotes* produce mats freely floating on the surface of slow-moving or stagnant waters (Ceschin et al. 2016; Borsic and Rubinić 2021). *Lemna minuta* is native to temperate and subtropical regions of North and South America (Landolt 1986; Stace 2010) whereas *P. stratiotes* is native to tropical and subtropical regions across Africa, America, Asia and Oceania (Holm et al. 1977; GBIF 2023). Both species are regarded as invasive in various European countries (e.g., Hussner et al. 2014; Lukács et al. 2014; Ceschin et al. 2018a) (Table 2), although of the two species, only *P. stratiotes* was included in the list of IAS of Union concern (European Union 2022).

The bibliographic research for *L. minuta* identified a relatively little number of studies (27), with the majority addressing its impact (31%) and ecology (27.6%), and only a minimal part (3.4%) focusing on its management (Table 1; Fig. 3). Conversely, on *P. stratiotes* were found more studies (90), primarily concentrated on management (32%), while its impact was very little investigated (3%) (Table 1; Fig. 3).

Recent contributions on the management of *L. minuta* in Italy have mainly focused on biological control, particularly employing the small European lepidopteran *Cataclysta lemnata* Linnaeus, which appears effectively to control the alien plant during its herbivorous aquatic larval stage (Mariani et al. 2020, 2021). For controlling *P. stratiotes*, biocontrol practices were adopted utilizing the South American *Neohydronomus affinis* Hustache (curculionid beetle) in the Republic of Congo and South Africa (Mbati and Neuenschwander 2005; Coetzee et al. 2020) or the Argentine *Lepidelphax pistiae* Remes Lenicov (delphacid bug) in Argentina and Florida (Cabrera-Walsh and Maestro 2014; Goode et al. 2023). Practices of chemical control of *P. stratiote*s using synthetic herbicides, such as Carfentrazone-ethyl and Terbutryn, were also adopted in Florida and South Africa, respectively (Cilliers et al. 1996; Koschnick et al. 2004). While the use of Carfentrazone-ethyl is permitted in EU countries (European Commission 2025), the Terbutryn is prohibited, due to the risks of its release for the safety of the environment and human health (ECHA 2021).

Analyzing the contributions regarding the impacts (Table 1), it emerges that both species negatively influence the invaded aquatic ecosystem; indeed, these free-floating aquatic plants can create dense and compact mats that block light, oxygen, and heat from penetrating the water column below, affecting severely both abiotic (water chemical and physical factors) and biotic (native plant and animal communities) components (De Tezanos Pinto et al. 2007; Ceschin et al. 2019, 2020b; Jaklič et al. 2020). For example, tangible evidence in Europe of the direct impact by competition of the *L. minuta* with native plants is the partial or total replacement of the native congeneric *L. minor* in various waterbodies (Ceschin et al. 2016, 2018b; Gérard and Triest 2018). Other documented impact mechanisms include phytotoxicity through the production of allelopathic substances in *P. stratiotes* (Lv et al. 2022).

Ludwigia peploides, *L. hexapetala*, *L. grandiflora* (Onagraceae – rooted hydrophytes)

Ludwigia peploides, *L. hexapetala* and *L. grandiflora* are perennial herbaceous plants able to grow both in slow-flowing water and along the banks, exhibiting various morphotypes (floating creeping or erect emergent). These species, native to Central and South America, were introduced as ornamental plants in Europe where they were

recognized as invasive in some European countries (Table 2) (EPPO 2011; Buzjak and Sedlar 2018; Pelella et al. 2023a). However, only *L. grandiflora* and *L. peploides* are included in the list of IAS of Union concern (European Union 2016), while *L. hexapetala* is outside, even if it is closely related to *L. grandiflora*. Although there is debate on whether to consider *L. hexapetala* as a subspecies of *L. grandiflora* or as a separate taxon, in this review, *L. hexapetala* was considered to be a distinctive species from *L. grandiflora* (Armitage et al. 2013; Grewell et al. 2016; Barloy et al. 2024).

From the bibliographic research, 34, 49, and 23 contributions were found for *L. peploides*, *L. hexapetala* and *L. grandiflora*, respectively, with a main focus on ecological and management aspects of these species (Table 1). The most well-documented management methods include the use of both biocontrol agents, such as the chrysomelid beetle *Altica litigata* Fall in California and southern United States (Carruthers et al. 2011; Harms and Grodowitz 2012) and herbicides, such as Imazamox and Carfentrazone-ethyl, permitted also in EU countries (European Commission 2025), as documented in some studies conducted in North America (Enloe et al. 2020; Haug et al. 2023).

Studies on the impact of *L. peploides*, *L. hexapetala* and *L. grandiflora* account for 2.9%, 15.4% and 13%, respectively, of the total contributions collected for each of these species (Table 1). These studies primarily document environmental impacts on biotic components and only secondarily on abiotic ones. For example, one study conducted in France investigated the phytotoxicity of *L. peploides* exerted against native European plants, such as *Nasturtium officinale* R. Brown, producing allelochemicals (Dandelot et al. 2008). Likewise, *L. hexapetala* is known for producing allelopathic substances, mainly quercitrin, which can inhibit the growth of native plants in Europe, such as the aquatic carnivorous *Utricularia australis* R.Br. (Pelella et al. 2023b). In addition, a field study conducted in Italy documents for *L. hexapetala* both chemical and physical impacts on invaded aquatic ecosystems and competition with native aquatic plants, such as *Potamogeton nodosus* Poir., *Ceratophyllum demersum* L., *Callitriche stagnalis* Scop., *Chara hispida* L., and *Myriophyllum spicatum* L. (Pelella et al. 2023a). Studies on *L. grandiflora* in Belgium highlighted successful competition of this species with native plants and its negative influence on macroinvertebrate communities (Stiers et al. 2011; Stiers and Triest 2017).

The impact in Europe of these alien *Ludwigia* species is also significant from an economic viewpoint, due to the high costs incurred in managing them. In particular, Renault et al. (2021) provided a general overview of the expense (exceeding 700 million dollars) incurred in France between 1993 and 2018 for the management of some IAAPs, including these alien *Ludwigia* species.

Azolla filiculoides, *Salvinia molesta* (Salvinaceae – free-floating hydrophytes)

Azolla filiculoides and *S. molesta* are free-floating aquatic ferns native to Central and South America (Svenson 1944; Coetzee and Hill 2020). Introduced across much of Asia and Europe (Table 2), they have become here highly invasive due to their effective vegetative and sexual reproduction through spores. This enables them to spread quickly, increase significantly biomass and form dense free-floating mats on the surface of invaded waterbodies (Janes 1998; Hussner 2010; Koutika and Rainey 2015). *Salvinia molesta* is considered as one of the world's worst invasive alien species, posing a severe threat to the conservation of freshwater ecosystems (Lowe et al. 2000;

Courchamp 2013), and it is listed as an IAS of Union concern (European Union 2019). Conversely, *A. filiculoides* is not included in this Union list, although it is listed as alien invasive species in national lists of several European countries (e.g. Szczesniak et al. 2009; Arianoutsou et al. 2010; Galasso et al. 2018). Based on bibliographic research, 71 and 40 contributions were found for *S. molesta* and *A. filiculoides*, respectively, with most part of these focused on management activities through chemical and biological control of these two species (40.3% and 35.7%, respectively) (Fig. 3). In particular, chemical control was mainly tested in South America, using Imazamox for *Salvinia* (Garlich et al. 2021), and in Iran, using 2,4-D for *Azolla* (Nosratti et al. 2020), both herbicides permitted in Europe (European Commission 2025). As regards biological control, some herbivorous insects were successfully used, such as the Brazilian curculionid *Cyrtobagous salviniae* Calder and Sands in Texas and Louisiana against *Salvinia* (Tipping et al. 2008), and the American curculionid *Stenopelmus rufinasus* Gyllenhal in United Kingdom against *Azolla* (Reeder et al. 2018). Some applicative studies on *S. molesta* (13%) emphasize its utilization as fertilizer, biofuel, and inspiration in biomimetic applications, exploiting the unique structural features of the hydrophobic hairs on its fronds (Hussain et al. 2016; Kakunuri et al. 2017). As for *A. filiculoides*, its use as animal feed and phytoremediation agent was well documented (e.g., Leterme et al. 2009; Kösesakal et al. 2016). A notable proportion of ecological studies (19%) on this species of *Azolla* was found (Table 1).

For both *S. molesta* and *A. filiculoides*, about 9% of the contributions collected document impacts caused by these two species. In particular, environmental impacts are the most frequently investigated, even if a small number of studies conducted in India on *S. molesta* has also highlighted the not-negligible socio-economic impact of this species on human activities, such as shipping, fishing and agriculture (Retnamma et al. 2023). For *S. molesta*, the main environmental impact mechanism involves alterations to abiotic components of the invaded ecosystem, with particular reference to the water chemical factors. In fact, as it was documented in some studies in Louisiana and Puerto Rico, the dense free-floating mats formed by this species impede gas exchange at the air-water interface, resulting in reduced oxygen levels and lower pH in the underlying water column (Wahl et al. 2020, 2021a). Other studies highlighted direct impacts both on native flora by interspecific competition (Wahl et al. 2021b) and on the complexity and biodiversity of aquatic insect communities in Louisiana (Wahl et al. 2021c). Similar abiotic impacts, as well as competition with native aquatic plants and phytoplankton and negative interactions with animal organisms (in particular zooplankton and amphibians), were documented in Europe for *A. filiculoides* (Paolacci et al. 2018; Pinero-Rodríguez et al. 2019, 2021).

Hydrocotyle ranunculoides (Araliaceae – rooted hydrophyte)

Hydrocotyle ranunculoides is a rooted hydrophyte with floating and emergent leaves that is able to form dense monospecific mats on the surface of slow-flowing waters (Huckle 2002). Native to North America, it was introduced to Africa, Asia, Australia and also to Europe (Cabrera-Walsh et al. 2013), where it was listed among the IAS of Union concern (European Union 2016). From bibliographic research few contributions (19) were collected on this species (Fig. 3). The contributions focused on ecological, distribution and management aspects were found to be prevalent. The most frequently tested methods for controlling the spread of

this species were both biological control, mainly using curculionid beetles, such as *Listronotus elongatus* Hustache, in a study conducted in Buenos Aires (Argentina) (Cabrera-Walsh et al. 2013), and physical control, involving high-pressure hot water spraying on plants to increase their mortality (Bradbeer et al. 2021). Some studies analyzed the environmental impacts of *H. ranunculoides*, revealing its capacity not only to compete with native plants, such as *Utricularia vulgaris* L. and *Hydrocharis morsus-ranae* L. in Belgium, but also to induce changes in macroinvertebrate communities and chemical and physical parameters of the invaded aquatic ecosystem (Stiers et al. 2011; Stiers and Triest 2017). A study documents how dense and extensive populations of this species in stagnant waters in Zimbabwe can have a strong negative impact on the local aquatic birds, particularly on those species that require open waters for fishing their prey (Simbanegavi et al. 2018).

Alternanthera philoxeroides (*Amaranthaceae* – rooted hydrophyte)

Alternanthera philoxeroides is a perennial herbaceous plant native to the temperate regions of South America (Julien et al. 1995). It is recognized as one of the world's worst invasive aquatic plants, able to colonize both aquatic and riparian habitats (Willingham et al. 2015). This species is inserted in the list of the IAS of Union concern (European Union 2017), even if it does not show a wide distribution in Europe (Table 2).

The bibliographic research revealed a substantial number of contributions (312) related to this species, placing it among the most studied IAAPs among those considered (Fig. 3). Most of the contributions are related to ecological (34%) and biological studies (19.8%) (Table 1). Contributions focused on practices for managing *A. philoxeroides* (9.8%) highlight that chemical and biological control are the most utilized methods to counteract the spread of this species (Willingham et al. 2015; Chu et al. 2019; Knight and Harms 2022). In particular, for chemical control, some studies in Texas (USA) document the application of herbicides, such as Penoxsulam, Triclopyr and Bispyribac-sodium, the last of which is banned in the EU (European Commission 2025). As regards biological control of *A. philoxeroides*, there are studies on the use of the South American thrip *Amynothrips andersoni* O'Neill in the southeastern USA and of the lepidopteran *Herpetogramma basalis* Walker in China, where it is native.

Though constituting a minority (11%) of the total contributions collected for *A. philoxeroides*, the 36 studies focused on its impact are numerically significant. These studies document both socio-economic and environmental impacts on the abiotic and biotic components of the invaded ecosystem. The socio-economic impact is due to both large amount of biomass that this species produces, consequently limiting aquaculture and fishing activities, and to high costs that are necessary for the removal and disposal of this pest species as special waste (Keller et al. 2018). As regards environmental impacts, it was observed that competition with native plants is the most extensively documented impact mechanism, often resulting in severe biodiversity losses, as it occurred in some areas of New Zealand, India and China (Bassett et al. 2012; Chatterjee and Dewanji 2014; Wu et al. 2017). Furthermore, cases of phytotoxicity due to the release of allelopathic substances by the species (Ge et al. 2018; Liu et al. 2020), as well as chemical and physical impacts on the invaded aquatic ecosystem (Yang et al. 2020; Zhang et al. 2020), were also documented in China.

Pontederia crassipes (Pontederiaceae – free-floating hydrophyte)

Pontederia crassipes (= *E. crassipes*) is a floating hydrophyte native to South America. It was introduced as an ornamental plant in many countries, including North America, Africa, Asia and Europe (EPPO 2008; Koutika and Rainey 2015), and it is now recognized as one of the world's worst IAS (Lowe et al. 2000). In Europe, where it shows a wide distribution (Table 2), it is listed as a species of Union concern (European Union 2016).

With 440 contributions, *P. crassipes* is the most studied IAAP among those considered (Fig. 3). Many studies (26.3%, 125 contributions) focused on finding effective methods to contain outbreaks of this species. Among these methods, biological control proved to be particularly promising. For example, South American curculionid beetles, such as *Neochetina bruchi* Hustache or *N. eichhorniae* Warner, were used as herbivore agents against this alien plant in Argentina (Faltlhauser et al. 2023) and in California (Pitcairn et al. 2021), respectively. The South American crambid moth *Niphograpta albiguttalis* Warren (Pitcairn et al. 2021) was also tested in California. In a laboratory study, the combined effect of various biocontrol agents was analyzed, among which the aforementioned curculionid beetles, galumnid mites (*Orthogalumna terebrantis* Wallwork) and phytopathogenic fungi (*Fusarium oxysporum* Schlecht, *F. roseum* Link, *Paradendryphiella salina* (G.K. Sutherl.) Woudenb. & Crous) (Dutta and Ray 2017). Physical and chemical control methods were also documented; for instance, mechanical removal of *P. crassipes* was carried out on the Burdekin River in Australia (Perna et al. 2012), while chemical control included the use of Glyphosate in Puerto Rico and Florpyrauxifen-benzyl in the United States (Mudge et al. 2021; Robles and Martínez 2021), whose use of both is permitted in Europe (European Commission 2025). Many of the contributions found are focused on applicative uses of the species (25.8%, 123 contributions), mainly highlighting its potential as a bioenergy source (e.g., Santos et al. 2015; Peng and Slocum 2020); indeed, the substantial biomass it produces can be used as biofuel, replacing conventional fossil fuels. In addition, it can offer a promising alternative as animal feed and compost (Hronich et al. 2008; Lin et al. 2015; Rezania et al. 2015; Patwa et al. 2022).

Many contributions on the impact of *P. crassipes* (11.3%, 54) document negative influences on both biotic and abiotic component of the invaded ecosystem. Competition with native vascular plants and algae is the most frequently reported impact mechanism, such as in some studies conducted in China and India (Zhou et al. 2017; Lv et al. 2022; Lahon et al. 2023; Shen et al. 2023). Cases of phytotoxicity against terrestrial plants, such as *Lepidium sativum* L., *Lactuca sativa* L., *Medicago sativa* L., *Phleum pratense* L. and *Lolium multiflorum* Lam., were observed in a laboratory study (Kato-Noguchi et al. 2014). Alterations to native macroinvertebrate communities in South Africa and impacts on aquatic birds and fish in the Lake Cluster of Pokhara Valley in Nepal (Coetzee et al. 2014; Basaula et al. 2021, 2023) were also documented. Extended and dense free-floating populations of *P. crassipes* are also able to change water chemical and physical properties, increasing conductivity and reducing dissolved oxygen, pH and light penetration in the invaded waterbodies (Gezie et al. 2018). Such dense populations can cause a serious socio-economic impact to local human populations, as they negatively affect agriculture and waterbodies navigability, as it occurred in Ghana (Honlah et al. 2019). In addition, as reported by Heringer et al. (2021), the 179.9 million dollars spent between 1975 and 2020 for the eradication of *P. crassipes* in Central and South America, makes this species the most expensive aquatic taxon to manage.

Myriophyllum aquaticum, *M. heterophyllum* and *Cabomba caroliniana* (Haloragaceae and Cabombaceae – rooted hydrophytes)

All species of this group are rooted hydrophytes and, while *Myriophyllum aquaticum* and *C. caroliniana* are native to South America, *M. heterophyllum* is native to North America (Orgaard 1991; Schooler et al. 2009; Moody and Les 2010). In Europe, all three species are considered highly invasive and are included in the list of IAS of Union concern (European Union 2016, 2017).

The bibliographic research on these species found a total of 70 contributions for *M. aquaticum*, 16 for *M. heterophyllum* and 38 for *C. caroliniana* (Fig. 3). Management and ecological aspects are the most extensively investigated for all three species (Table 1). Contributions on the management of *M. aquaticum* and *C. caroliniana* document that chemical and biological control are the most frequently used methods. In particular, in some studies conducted in the northern United States various herbicides were utilized, such as Carfentrazone and 2,4-Dichlorophenoxyacetic acid (2,4-D) (Bultemeier et al. 2009; Kuehne et al. 2018), the use of which is also permitted in Europe (European Commission 2025). As regards biological control methods, different biological agents were tested, such as the competitive native aquatic plant *Nymphoides indica* (L.) Kuntze in Australia (Nguyen et al. 2021), the phytophagous chrysomelid beetle *Lysathia* sp. in South Africa (Hill and Coetzee 2017) and the curculionid *Hydrotimetes natans* Kolbe in Australia (Cabrera-Walsh et al. 2011). Some physical methods, such as manual removal of biomass and shading the plant populations by extensive coverings (Bailey and Calhoun 2008; Getsinger et al. 2008), were documented for *M. heterophyllum*.

From bibliographic research, it emerges that in very few contributions was analyzed impact of these species (Table 1). However, among these contributions, some performed in Canada and Belgium document for all three species an environmental impact expressed through competition with native plants (Hogsden et al. 2007; Stiers et al. 2011; Smith et al. 2021). In addition, *M. aquaticum* can cause a chemical impact with a reduction of the concentration of dissolved oxygen in invaded ponds, as showed in a study conducted in Belgium (Stiers and Triest 2017), while *M. heterophyllum* can exert an impact through hybridization with native congeneric species in North America (Moody and Les 2002). *Cabomba caroliniana* is proved to be the cause of a physical impact on a lake in Ontario, due to significant light reduction in the water column beneath the dense populations produced (Hogsden et al. 2007). For *M. heterophyllum*, a socio-economic impact was also documented. Indeed, Halstead et al. (2003) noted that in the American state of New Hampshire, where *M. heterophyllum* is considered an alien weed since that is not part of its native aquatic flora before 1950, the value of properties near lake shores infested by this species is significantly lower than similar properties in non-infested lakes, negatively affecting the local economy.

Elodea canadensis, *E. nuttallii*, *Egeria densa*, *Lagarosiphon major*, *Hydrilla verticillata* (Hydrocharitaceae – rooted hydrophytes)

All species included in this group are obligate rooted hydrophytes (Bowmer et al. 1995). *Elodea canadensis* and *E. nuttallii* are native to North America (Zehnsdorf et al. 2015; Buldrini et al. 2022), *E. densa* to South America (Rimac et al. 2018), *L. major* to South Africa (Baars et al. 2010) and *H. verticillata* to Asia and Australia

(Cook and Lüönd 1982). Despite being recognized as highly invasive in various European countries (Table 2), only *L. major* and *E. nuttallii* are listed as IAS of Union concern (European Union 2016, 2017). With 201 and 270 contributions, *E. densa* and *H. verticillata* are among the most studied IAAPs. However, the other species of this group have also received considerable attention, particularly on their ecological aspects (Fig. 3). Contributions on management are numerous, especially for *L. major* (35.3%) and *H. verticillata* (27.4%). Conversely, *E. densa* and *E. canadensis* have few studies on this topic (10%) (Table 1). The management methods documented for these species include mainly chemical and physical control. As for chemical control, the use of synthetic herbicides was documented, such as Diquat for *E. densa* in Brazil and Connecticut (Martins et al. 2008; Bugbee et al. 2020), Flumioxazin for *E. canadensis* in New Zealand (Hofstra et al. 2021) and Endothal and Florpyrauxifen-benzyl for *H. verticillata* in United States (Ortiz et al. 2022). The use of Diquat and Endothal is prohibited in Europe (European Commission 2025). Physical control was used especially against *E. nuttallii* by adding biodegradable dyes in water or applying shading cover to reduce light availability and inhibit plant growth (Hoffmann et al. 2013; Zefferman 2014). In addition, cases of biocontrol were documented, such as the use of the Asian fly *Hydrellia pakistanae* Deonier against *H. verticillata* in Florida (Wheeler and Center 2001) and *H. lagarosiphon* Deeming against *L. major* in Ireland (Mangan and Baars 2023). Despite the substantial number of contributions found for this group of species, the studies analyzing their impact prove to be relatively few (Table 1). The most documented impact mechanisms for these species are both chemical and physical, as it occurred in some invaded waterbodies of Ireland, Norway and France (Mjelde et al. 2012; Kelly et al. 2015; Ribaudo et al. 2018), and competitive with native plants, as observed for *H. verticillata* in South America, *E. densa* in California and *E. canadensis* in Norway (Santos et al. 2011; Mjelde et al. 2012; Silveira et al. 2018). In addition, some studies document that *E. densa* has a negative impact on native plants in China (Dai et al. 2023), while *E. nuttallii* and *L. major* affect native European plants by releasing allelopathic substances that inhibit their growth (Erhard and Gross 2006; Cuthbert et al. 2020).

Gymnocoronis spilanthoides (Asteraceae – emergent rhizophytes)

Gymnocoronis spilanthoides, native to South America (Tippery et al. 2014), was introduced as an ornamental aquarium plant in East Asia, Australia, New Zealand and Europe. In Europe, although it occurs in few countries (Table 2), it is considered invasive (Lukács et al. 2014; Ardenghi et al. 2016) and was included in the list of IAS of Union concern (European Union 2019). Bibliographic research revealed very few studies on this species, counting only five published contributions mainly focused on its ecology (Table 1; Fig. 3). No contributions related to the impact or management of this species was found.

Discussion

Critical literature analysis

The bibliographic research on the main European IAAPs showed that the scientific knowledge gained worldwide on these species is unequal. It is focused only on certain species (*P. crassipes*, *A. philoxeroides*, *E. densa*, *H. verticillata*) and very scarce

and fragmented on others (*G. spilanthoides*, *H. ranunculoides*, *L. minuta*, *M. heterophyllum*, *L. grandiflora*, *L. peploides*). Such knowledge inequality is a phenomenon already documented in literature and can be attributed to a combination of factors. As highlighted by Pyšek et al. (2008), geographical, socio-economic and taxonomic biases can play a crucial role in driving knowledge on invasion ecology. Species that invade regions of greater socio-economic interest, such as Europe or USA, and those belonging to taxa that are better known or perceived as more impactful, generally tend to receive more attention. This may explain why species, such as *P. crassipes* or *S. molesta*, which are known to be impactful, are the target species of numerous studies globally, while others, such as *G. spilanthoides*, which are less widespread in relevant regions, or perhaps perceived as less problematic, remain relatively ignored. Furthermore, Hulme et al. (2013) pointed out that factors, such as the availability of research resources and the perception of an economic impact as a result of the invasion of an alien species, contribute to widening these disparities. Species with evident economic or ecological damage tend to catalyze scientific interest, explaining the observed differences in the knowledge between the considered IAAPs. This difference highlights on the one hand the need for more balanced research on these IAAPs and on the other hand the risk of underestimating the impact of less studied taxa.

This bibliographic research shows that most scientific contributions produced on the investigated IAAPs up to 2023 have primarily addressed ecological aspects and, secondarily, management strategies, often neglecting important topics, such as the impact exerted by these alien species on the invaded ecosystem. Indeed, the scientific production of studies analyzing the environmental impacts of these IAAPs turned out to be limited in numbers, often qualitative and deficient in field data. What is surprising is that for many of the IAAPs included in the list of Union concern (*G. spilanthoides*, *H. ranunculoides*, *L. peploides*, *L. grandiflora*, *P. stratiotes*, *C. caroliniana*, *M. heterophyllum*, *L. major*, *E. nuttallii*), there are only a few field studies evaluating the real extent and severity of their impacts on invaded ecosystem (Table 1). It is worth noting the importance of field studies that allow for collecting real data that are capable of showing what actually occurs in natural conditions, although sometimes the complex abiotic and biotic interactions may create confusion in the interpretation of the data itself. For this reason, laboratory studies, which however suffer from certain limitations, such as short time frames, reduced volumes and lower ecosystem complexity (Carpenter 1996; Schindler 1998), by reducing the variables to be analyzed, allow to focus only on what is experimentally important to evaluate. It is therefore evident that, in order to obtain a complete understanding of a phenomenon being investigated, it would be necessary to perform field studies combined with laboratory investigations.

Another important aspect emerging from this investigation is that for some of the IAAPs considered, such as *E. canadensis*, *L. minuta*, *A. filiculoides*, *L. hexapetala* and *E. densa*, despite various authors document their invasiveness and environmental impact in several European countries, they are not included in the list of IAS of Union concern. Consequently, in Europe, these species might evade any type of controls of their commercialization, on free use, or of release into the environment. The reason why these IAAPs are not yet included in this EU list might only be a matter of time. Indeed, the scientific documentation on their impacts in Europe may still be under evaluation by the European Commission, which may not allow for regulated and coordinated European actions against these

species to date. However, some of these IAAPs, such as *A. filiculoides*, *E. canadensis* and *E. densa*, are included in legally regulated national lists (e.g., Spanish Catalogue of IAS by Spanish Ministry of Agriculture, Food and Environment 2013 - Royal Decree 630/2013). The promulgation of these national catalogues allows the member states of the European Community to manage IAS that pose a threat to conservation of the national territory, even if not prioritized at European level.

Understanding how (mechanism) and how much (severity) an IAS exerts on impact is fundamental to accurately assessing whether that species, despite being locally widespread, poses a real threat to the conservation of native biodiversity and integrity of the ecosystem invaded. Should significant evidence emerge regarding the danger of a species, it becomes imperative to promptly contain its spread. This involves promoting prevention campaigns, as well as monitoring, field study, and eradication activities, to prevent ecosystem damage and management costs from becoming unsustainable. For example, with reference to the latter aspect, a study conducted in Spain showed that the management of *P. crassipes* alone cost approximately 55 million dollars between 1997 and 2019 (Angulo et al. 2021). Furthermore, an estimate by Cuthbert et al. (2021) on data published from 1971 to 2020 on IAAPs, revealed that the overall management of IAAPs cost the global economy more than 20 billion dollars.

Temporal analysis of the collected literature

The number of contributions on the impact of the considered IAAPs increased exponentially from 1980 to 2023, with a particular peak in recent years (2016–2023) (Fig. 2a). This trend is aligned with both the increasing number of introductions of alien species outside their native ranges (Seebens et al. 2017), and the awareness of researchers of the serious impacts that invasions of these species can entail on ecosystem conservation. Based on these considerations, and limiting the analysis to the studies carried out in Europe on the IAAPs included in the list of IAS of Union concern (from 2016 onwards), one would have expected that the number of contributions on the impact and management on these species would increase once they were included in the list; in fact, the inclusion of an alien species in this list should entail the acquisition of the status of potential environmental threat, such that investigations, monitoring and control activities should be intensified. Instead, contrary to what was expected, the results showed that scientific production in Europe on the impact and management of these species was not much affected by the "listing" effect; indeed, for most of the species, after being included into the EU list, only a slight increase was recorded (minimal "listing" effect) or even a decrease or absence (no "listing" effect) of European studies about (Table 3).

Based only on European studies found on the impact of the selected IAAPs, and distinguishing between included and not-included species in the EU list, it emerged that the first group was on average less studied than the second (Fig. 4). This underlines once again that a species, even if included in the EU list, has not necessarily been the target of greater scientific interest in Europe, although the opposite would have been expected. Furthermore, the higher average number of contributions focused on the non-listed IAAPs, whose environmental impact was often documented by scientific evidence, should suggest a future consideration of these species in the list updates of IAS of Union concern.

Analysis of IAAPs impact mechanisms

The investigated IAAPs were found to affect both abiotic and biotic component of invaded aquatic ecosystems. Impacts on abiotic component occur when these plants alter physical (physical impact) and chemical (chemical impact) properties of the ecosystem invaded, consequently affecting indirectly the composition and diversity of the native plant and animal communities. For instance, it is well documented that free-floating alien hydrophytes, such as *A. filiculoides*, *L. minuta*, *S. molesta* and *P. stratiotes*, form dense populations on the water surface and thus modify water physically (e.g., light, temperature) and chemically (e.g., dissolved oxygen, pH, nutrients), thus indirectly compromising the survival of native plant and animal communities (e.g., Pinero-Rodríguez et al. 2019, 2021; Wahl et al. 2021c; Lv et al. 2022).

The mechanisms of impact were found to mainly result from interspecific competition for light and nutrients with native plants, often resulting in the dominance of invasive species over native ones (e.g., Ceschin et al. 2016, 2020b; Paolacci et al. 2018; Jaklič et al. 2020; Wahl et al. 2021b). Rooted alien hydrophytes, such as *E. canadensis*, *E. nuttallii* and *P. crassipes*, can produce dense and monospecific populations that replace native plant communities, reducing local plant diversity and simplifying plant community structure (Bubíková et al. 2021; Lahon et al. 2023). It was also demonstrated that extensive populations of *H. ranunculoides*, *M. aquaticum* and *S. molesta* lead to a structural simplification of the plant communities with serious consequences on macroinvertebrate communities, manifested by the decline of the most sensitive taxa and the survival of the most adaptable ones (Stiers and Triest 2017; Wahl et al. 2021c).

Another impact mechanism that was documented is linked to the phytotoxicity showed by some IAAPs that are able to produce and release allelopathic substances inhibiting the seed germination and/or growth of native aquatic plants. For example, *L. hexapetala* releases glycosidic substances (quercitrin) which inhibit vegetative growth of the native *Utricularia australis* (Pelella et al. 2023b). Similarly, *A. philoxeroides* releases allelochemicals affecting negatively the seed germinability of the native *Phragmites australis* (Cav.) Trin. ex Steud. and the vitality of the soil microbiota (Ge et al. 2018; Liu et al. 2020). Hybridization is another detected impact mechanism, whereby alien species cross with native species, producing hybrids that are more invasive than parental alien species. An example is *M. heterophyllum*, which hybridizes in several areas of the USA with the native congeners *M. hippuroides* Nutt. ex Torr. and A. Gray and *M. laxum* Schuttl. ex Chapm. (Thum et al. 2011).

Conclusions

This study found that the spread of IAAPs in Europe poses a significant threat to the conservation of European biodiversity and freshwater ecosystems. Despite growing awareness of the severity of the negative effect exerted by these species in invaded habitats, research focused on their environmental impacts and the ecological traits upon which their competitiveness and invasiveness are founded, remains limited to only a few invasive alien species. In such context, this investigation highlighted both the different treatment between IAAPs (listed and not-listed species in the Union list) and the inequalities that exist in the knowledge of their impact and management. In particular, some species have hardly been investigated at either the European or global level. Therefore, it is evident that there is a need to fill this knowledge gap and develop management practices that can contain the invasion of these

alien plants in Europe. Increasing field studies, possibly supplemented by laboratory tests, becomes essential to provide reliable data on the impact of these species. Such an approach, based on real data rather than simulations or potential impacts, will be able to contribute to a more effective management of the considered IAAPs, as well as improving the robustness of environmental conservation policies. In this regard, it is hoped that the species that are currently not listed but were found to be impactful and widely distributed in Europe (e.g., *E. densa*, *H. verticillata*, *L. minuta*, *E. canadensis*, *L. hexapetala*), are included in the list of IAS of Union interest as soon as possible. This will support consistent management practices at the European level, a crucial requirement for protecting the integrity of native communities and ensuring the proper sustainability and functionality of freshwater ecosystems in Europe.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

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Data availability

All of the data that support the findings of this study are available in the main text.

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